

# On the Spectral Dimensionality of Earth's Upwelling VSWIR Light Field

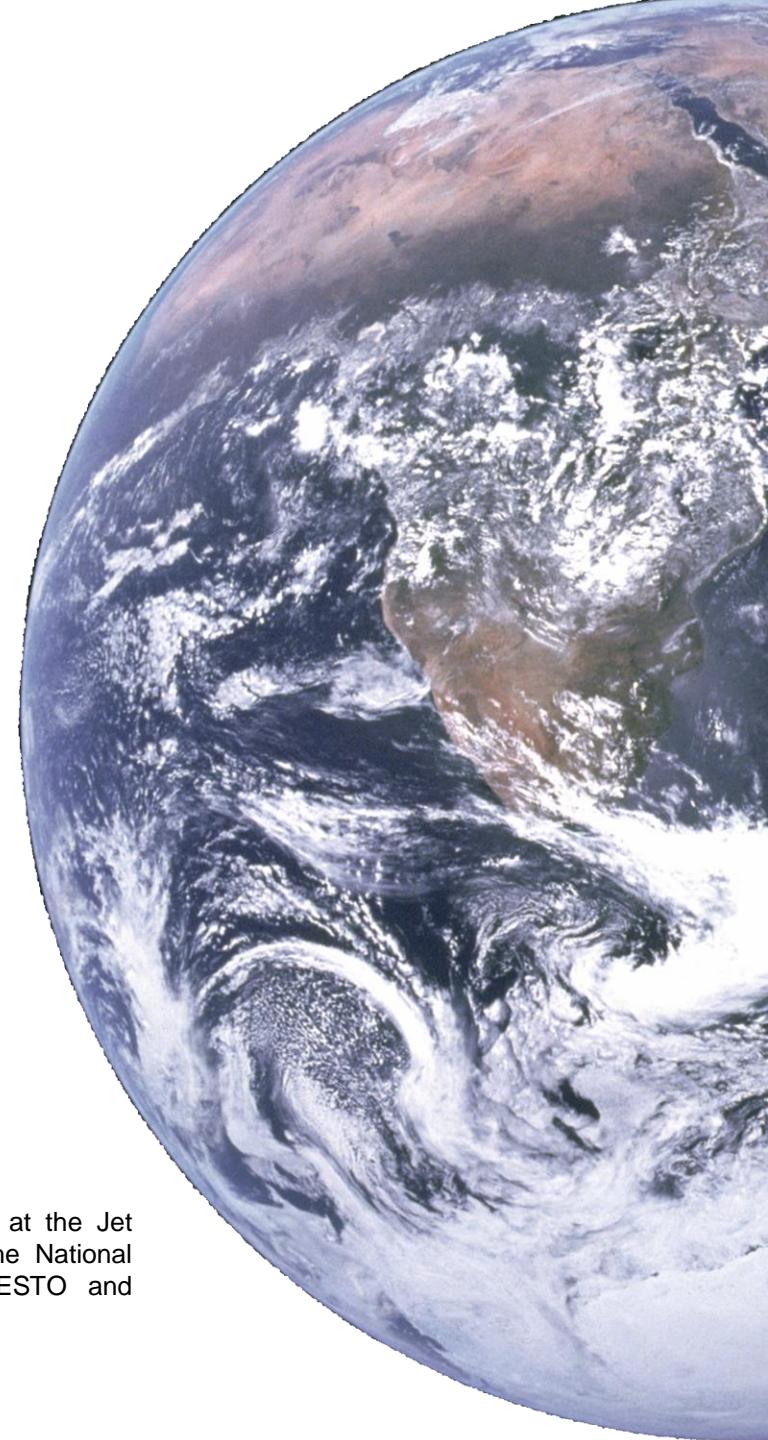
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Robert O. Green<sup>1</sup>, Michael Eastwood<sup>1</sup>

<sup>1</sup> Jet Propulsion Laboratory, California Institute of Technology

<sup>2</sup> Analytical Imaging and Geophysics, LLC



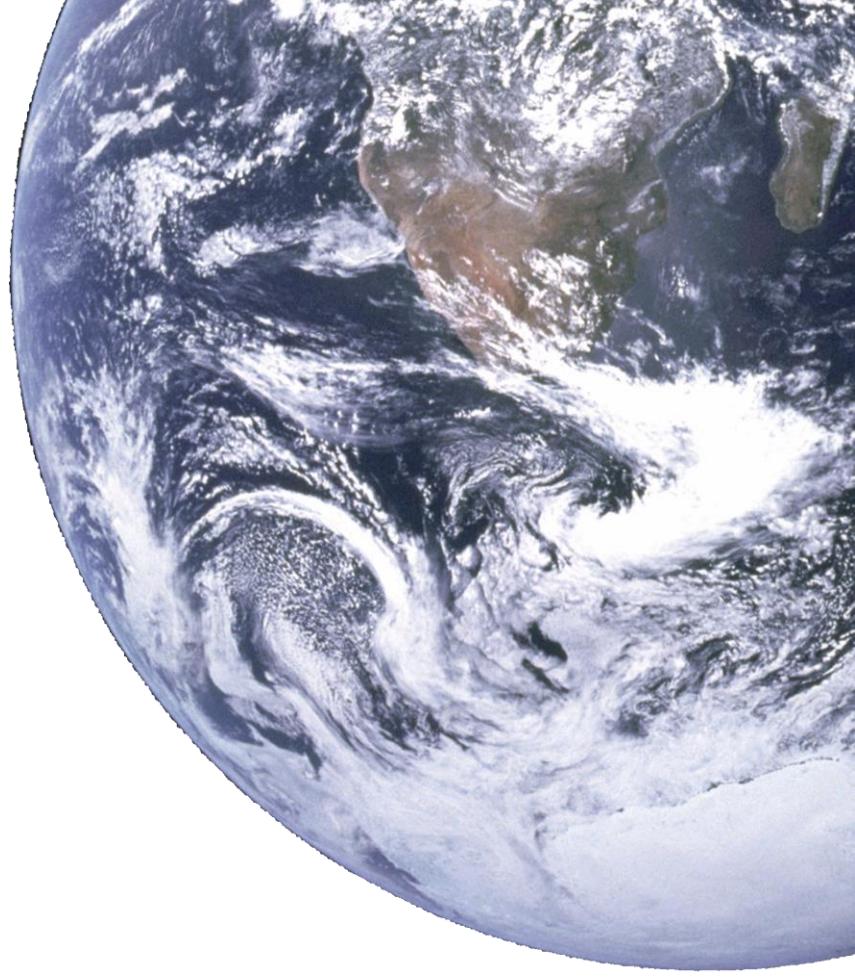
**Jet Propulsion Laboratory**  
California Institute of Technology



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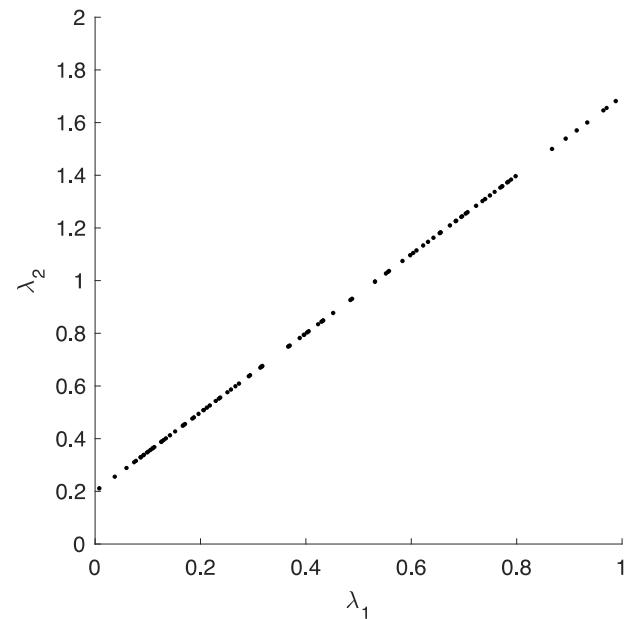
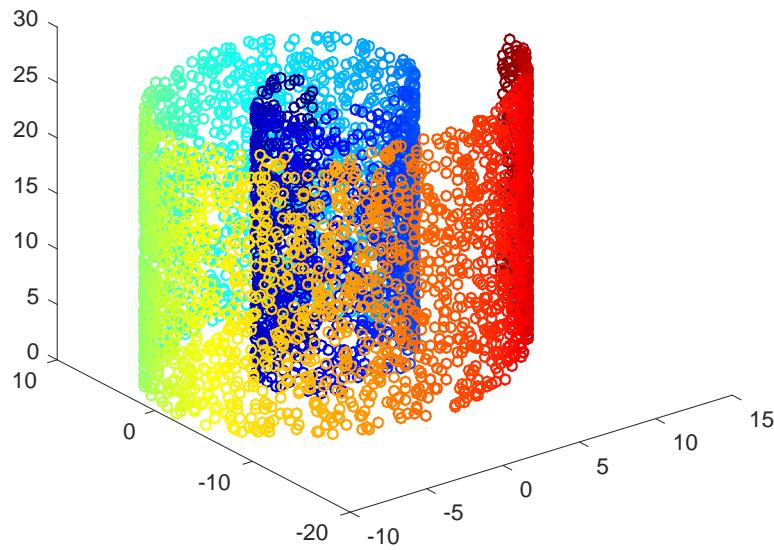
# Agenda

- What is intrinsic dimensionality?
- Methods for measuring dimensionality
- Results for the HyspIRI preparatory campaign
- Closing thoughts



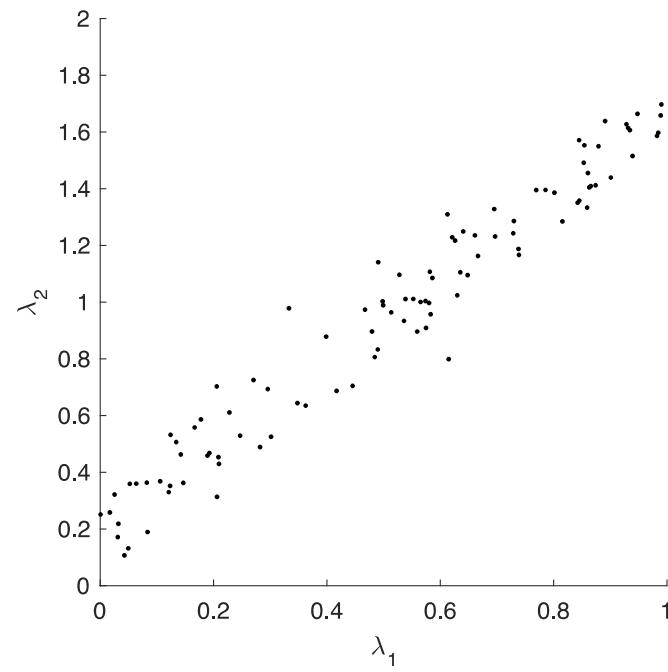
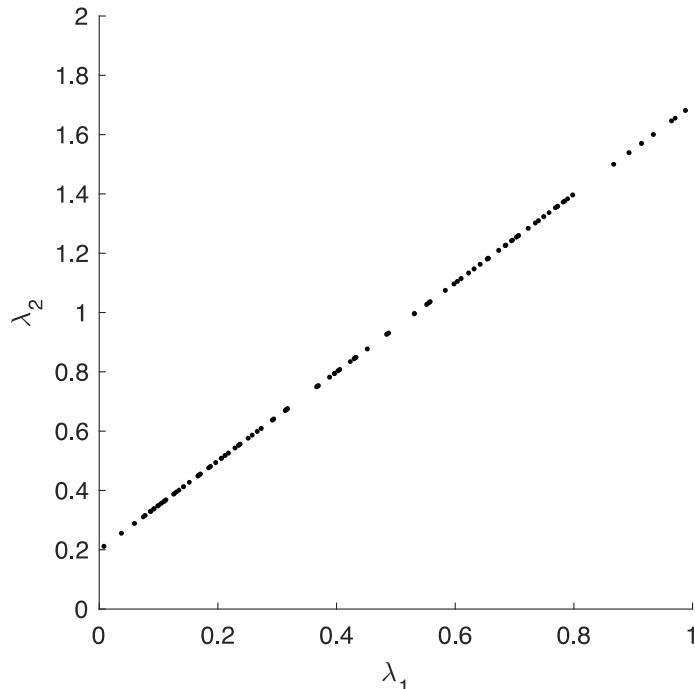
# Intrinsic dimensionality

- The degrees of freedom in a process under study
- Quantifies the measurable diversity in a dataset



Laplacian Eigenmap code via Kye Taylor, Mathworks file exchange

# Dimensionality estimates must account for measurement noise



Laplacian Eigenmap code via Kye Taylor, Mathworks file exchange



# Some ways to estimate dimensionality [Wu et al., Proc. SPIE 2006]

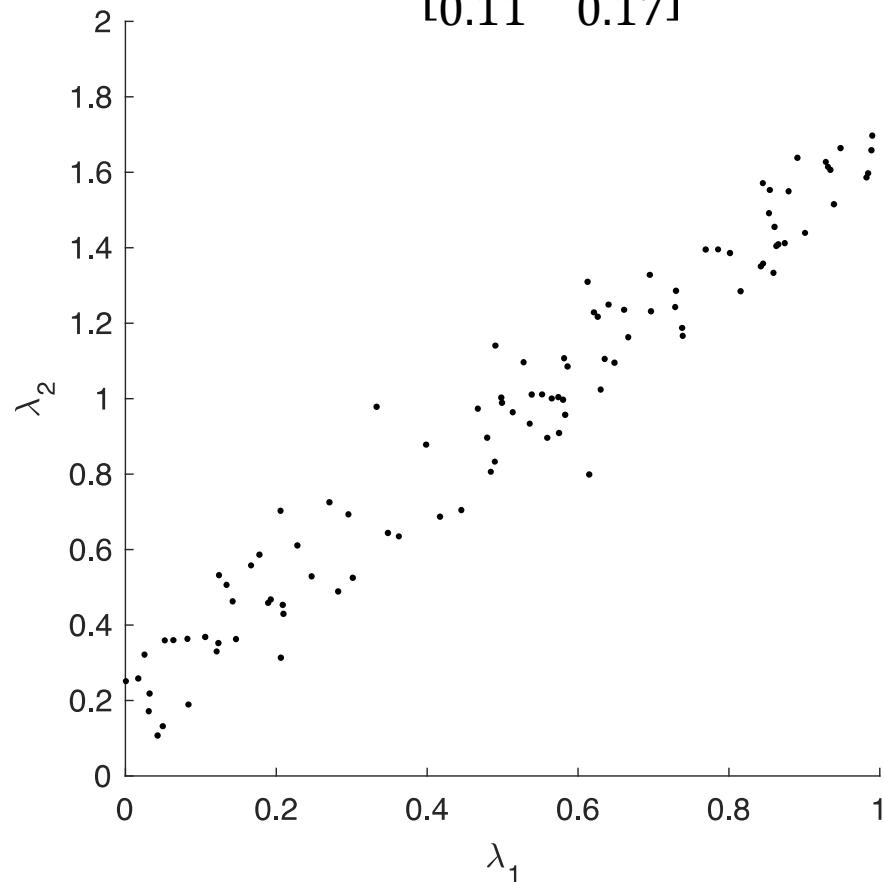
- Random Matrix Theory [K. Cawse-Nicholson, IEEE T. Image Process. 2013]
- Information Criteria [H. Akaike, IEEE T. Automat. Contr, 1974]
- Data Description Length [J. Rissanen, Automatica, 1978]
- Gershgorin Radii [Wu et al., IEEE T. Signal Proces, 1995]
- Signal Subspace Estimation [Bioucas-Dias and Nascimento, Proc. SPIE, 2005]
- Neyman-Pearson detection theory [Harsanyi et al., Proc. of Amer Soc. Photo. Rem. Sens, 1994]



# Covariance matrix eigenvalues

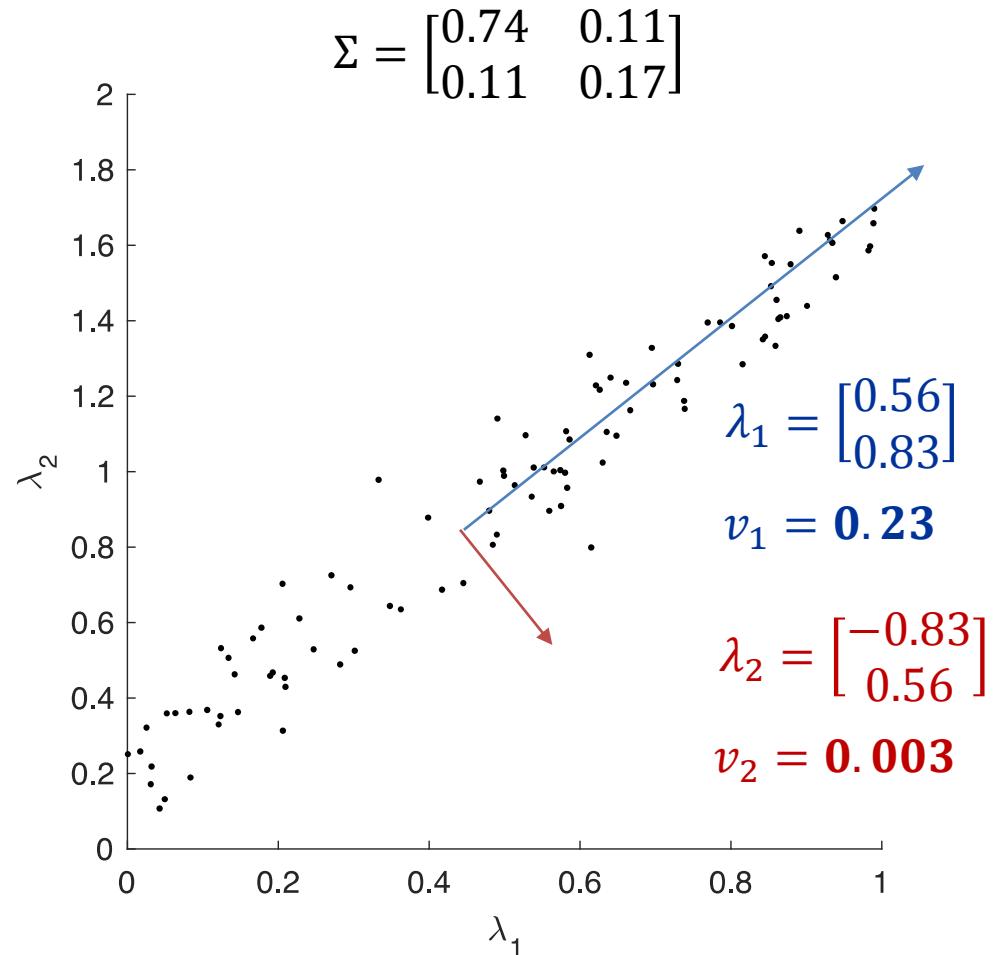
- Simple, pervasive in the literature
- Robust and repeatable
- Can be made objective and automated for application on large radiance datasets.

$$\Sigma = \begin{bmatrix} 0.74 & 0.11 \\ 0.11 & 0.17 \end{bmatrix}$$

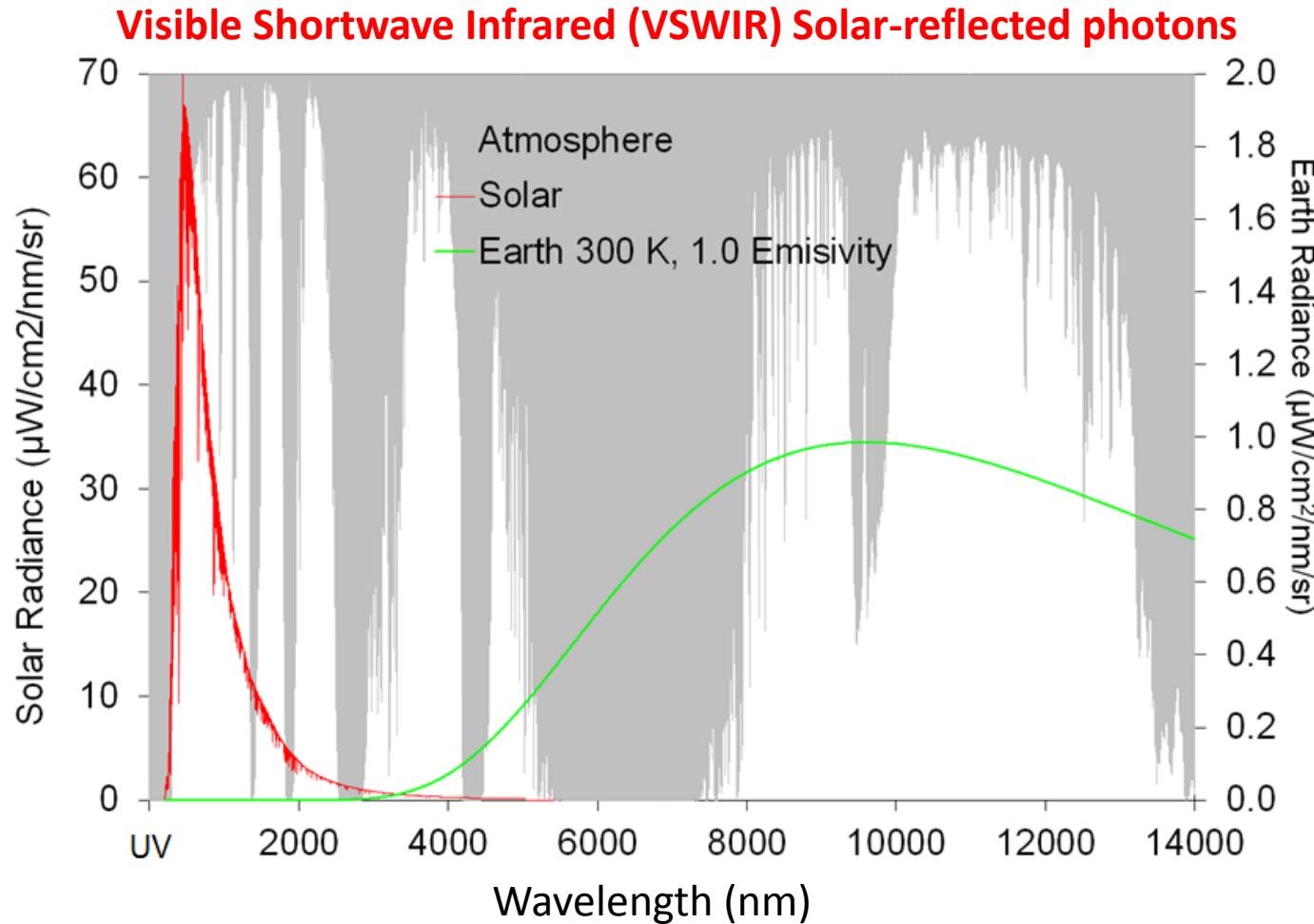


# Covariance matrix eigenvalues

- Simple, pervasive in the literature
- Robust and repeatable
- Can be made objective and automated for application on large radiance datasets.



# Dramatis Personae



# Many VSWIR applications

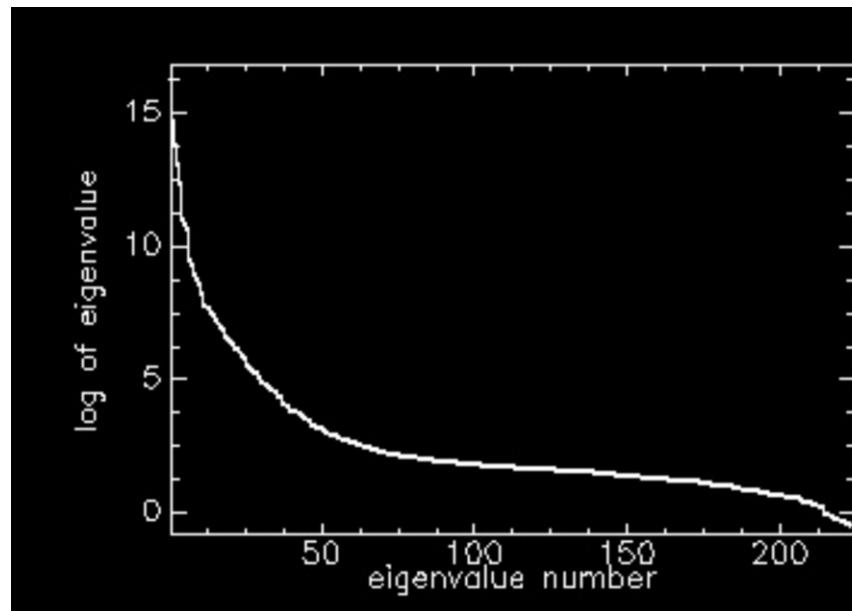
- **Aquatic ecosystems:** Condition and composition of benthic environments, water optical properties, phytoplankton, and water quality.
- **Vegetation and terrestrial ecosystems:** pigments, scattering and absorption in canopies, and absorption by structural elements, indicating plant health, structure, foliar chemistry and even species.
- **Solid surfaces** including natural mineralogy, artificial materials in urban environments.
- **Atmospheric constituents** including absorption by  $\text{H}_2\text{O}$ ,  $\text{O}_2$ ,  $\text{CH}_4$ ,  $\text{CO}_2$ , and scattering by aerosols.
- **Upcoming orbital missions** such as EnMAP, PRISMA, HISUI



# vSWIR dimensionality studies

- Diverse scenes: 20-50 [Boardman & Green 1999]
- Urban areas: 31-35 [Small, 2000]
- High spatial/spectral resolution: 100-200  
[Asner et al., 2012]

Eigenvalue decay of a large AVIRIS dataset  
[Boardman and Green, AVIRIS Workshop 1999]



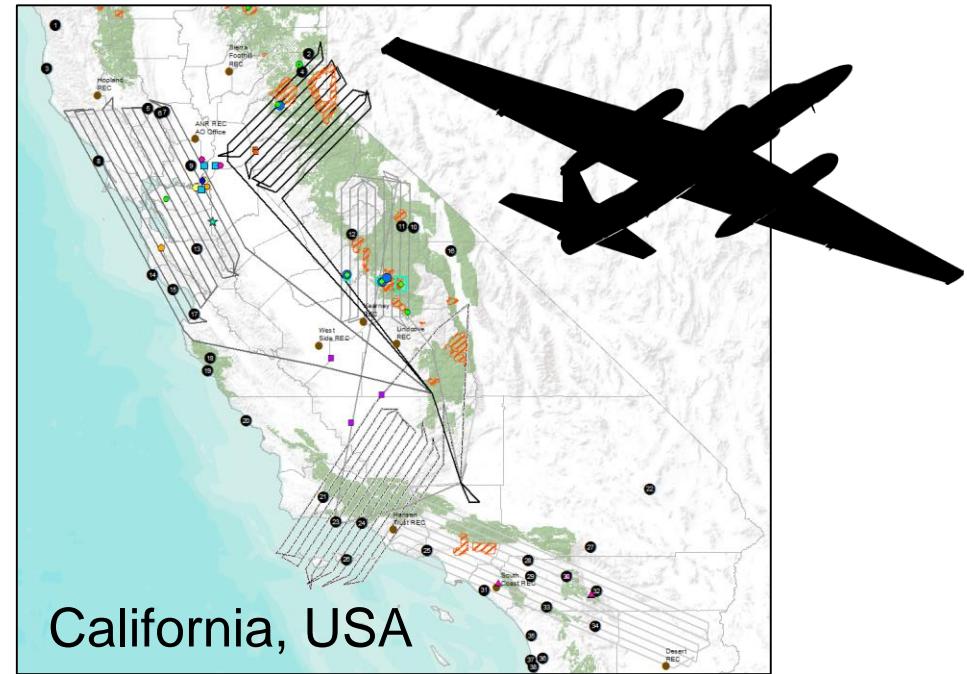
# Our Objectives

1. Characterize VSWIR dimensionality across a wide temporal and spatial range
2. Evaluate variability over space and time.
3. Use single sensor and spatial resolution similar to future orbital instruments.
4. Test the specific hypothesis of increasing spectral diversity in aquatic, terrestrial natural environments, and urban environments respectively.



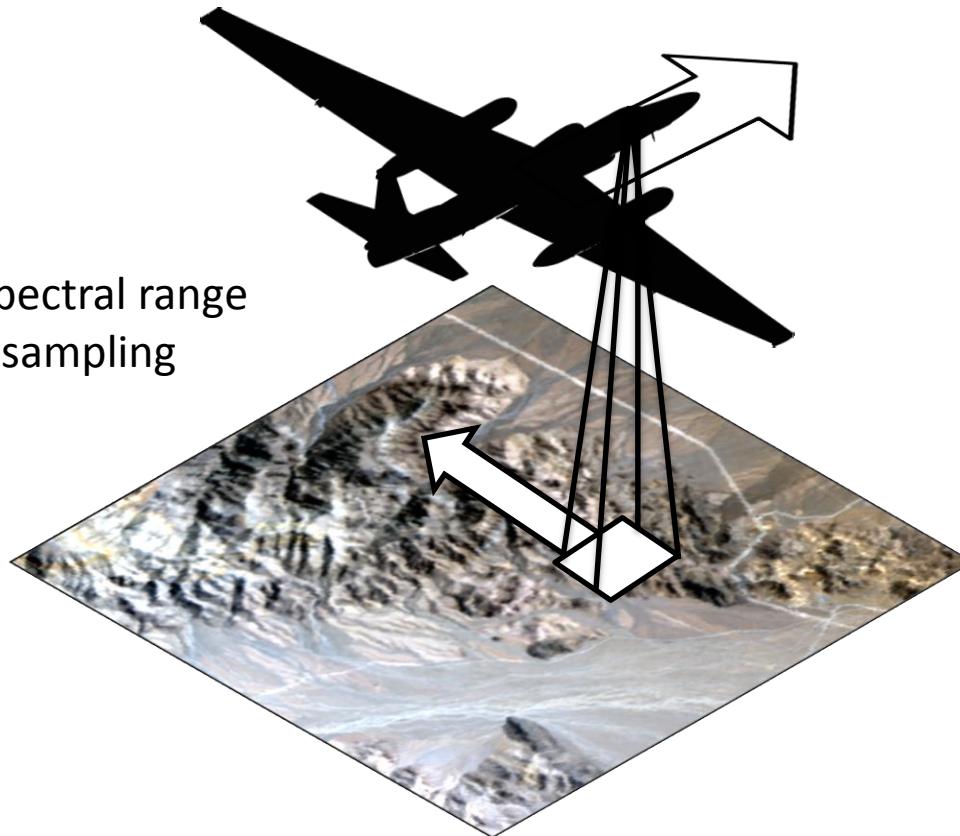
# NASA's Airborne Visible Infrared Imaging Spectrometer (AVIRIS-C) HyspIRI Campaign 2013-2014

- 20 km altitude
- 20 m spatial sampling
- 262 Flightlines
- Diverse biomes
- Diverse elevations
- 1.12 TB of data
- $2.5 \times 10^9$  spectra



# AVIRIS whiskbroom provides spatially uniform noise

380-2500 nm spectral range  
10 nm spectral sampling



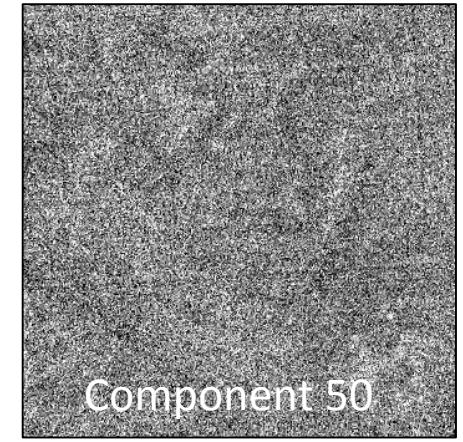
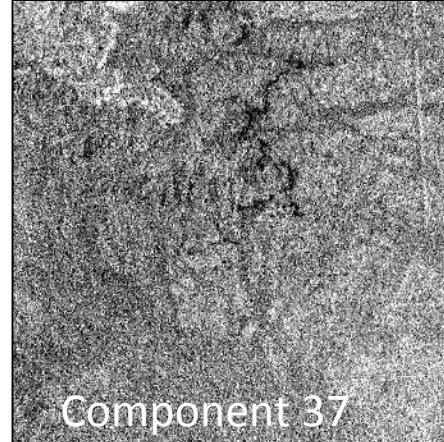
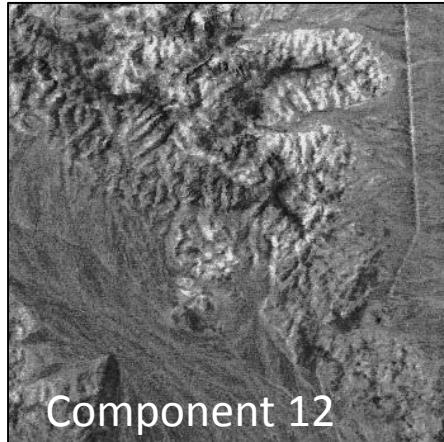
# Working definition

For a sample covariance  $\Sigma$  and sample sample mean  $\mu$ ,

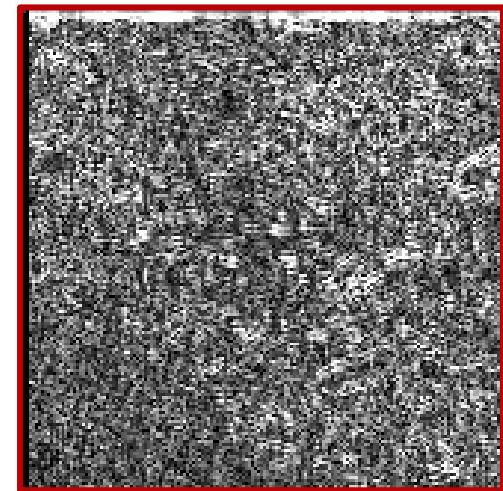
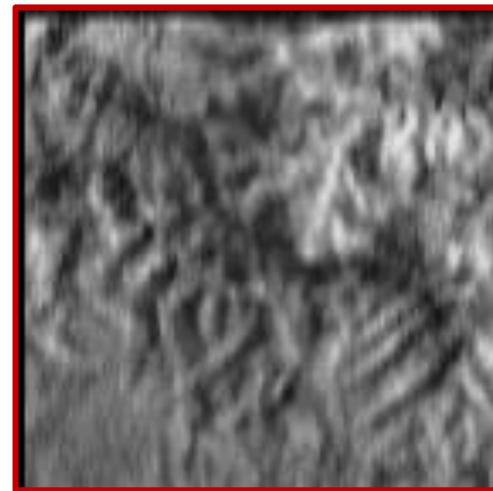
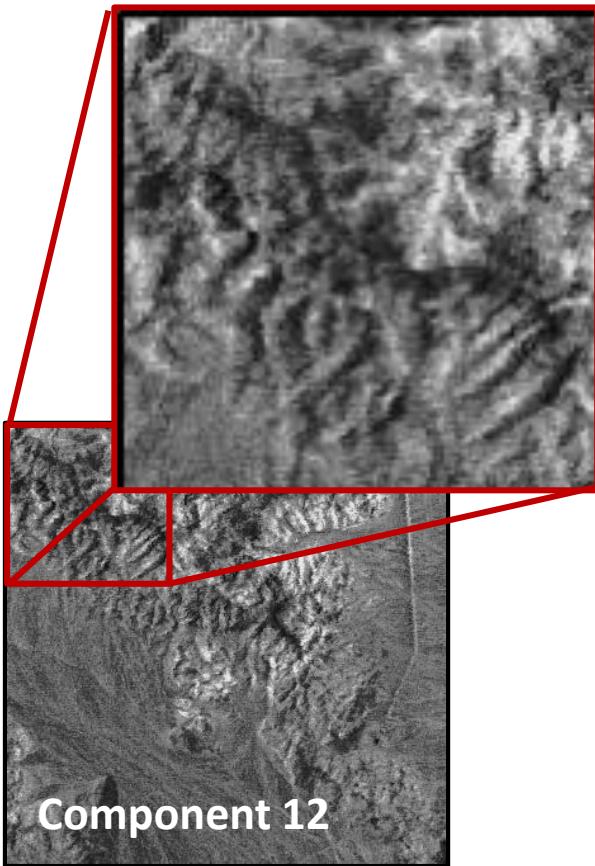
Use Singular Value Decomposition (SVD) to calculate orthogonal eigenvalues  $\lambda_i$  and eigenvectors  $v_i$

Find the projection of a radiance spectrum  $L_i$  onto each eigenvalue:

$$x_i = v_i^T (L_i - \mu)$$



# Measuring spatial structure



Downtrack smoothing acts like a *low-pass filter*. It estimates the spatially-correlated signal from scene

The remainder ( $\text{original} - \text{low pass}$ ) is a *high pass filter*. It estimates spatially-uncorrelated noise



Thompson et al., 2017, *Optics Express*, in press

# Dimensionality estimation approach - summary

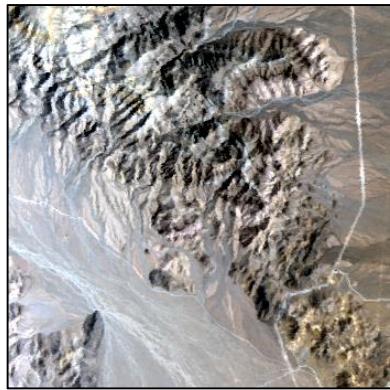
1. Decompose radiance data using Singular Value Decomposition
2. Apply a spatial smoothing operator to component projection images
3. Identify the spatially-correlated signal in each projection
4. Define dimensionality as the noise/signal crossover point, the top eigenvalue where spatially-uncorrelated noise dominates



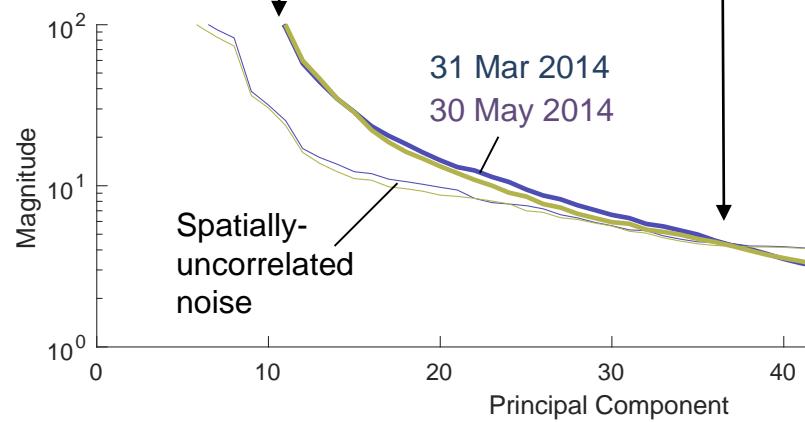
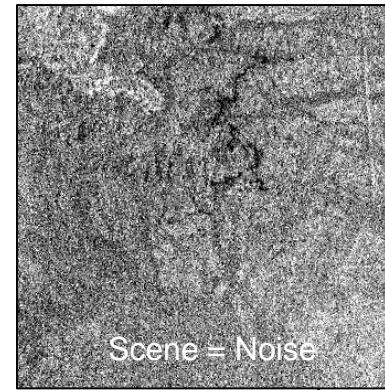
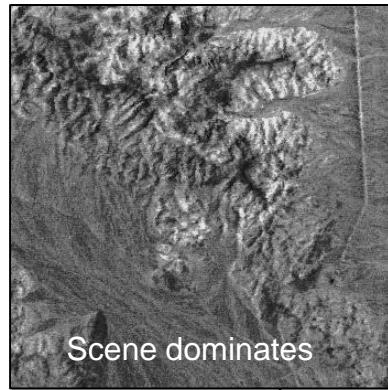
Ivanpah Playa validation site



# Eigenvalue decay curve example: Ivanpah Playa



R: 690nm  
G: 550nm  
B: 420nm



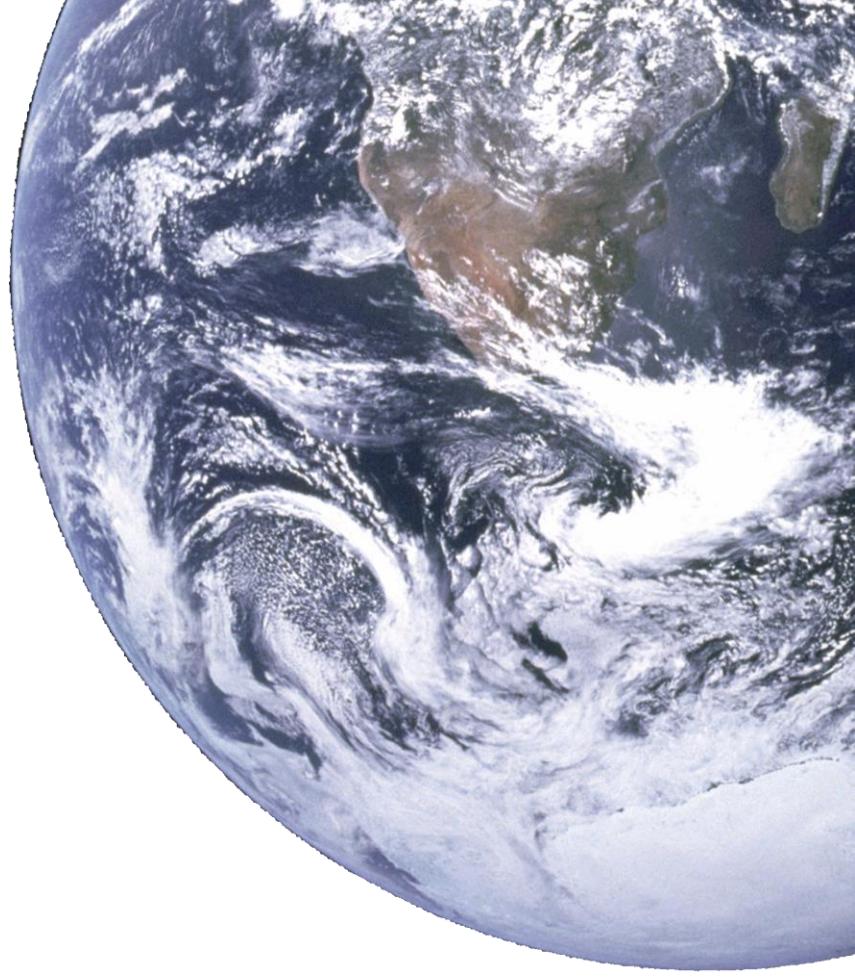
# Caveats

- Noise cutoff is a stable but conservative estimate (more spectra could be distinguished in practice)
- Second-order statistics do not reflect small, compact, rare outliers
- Our estimates depend on spectral and spatial resolution

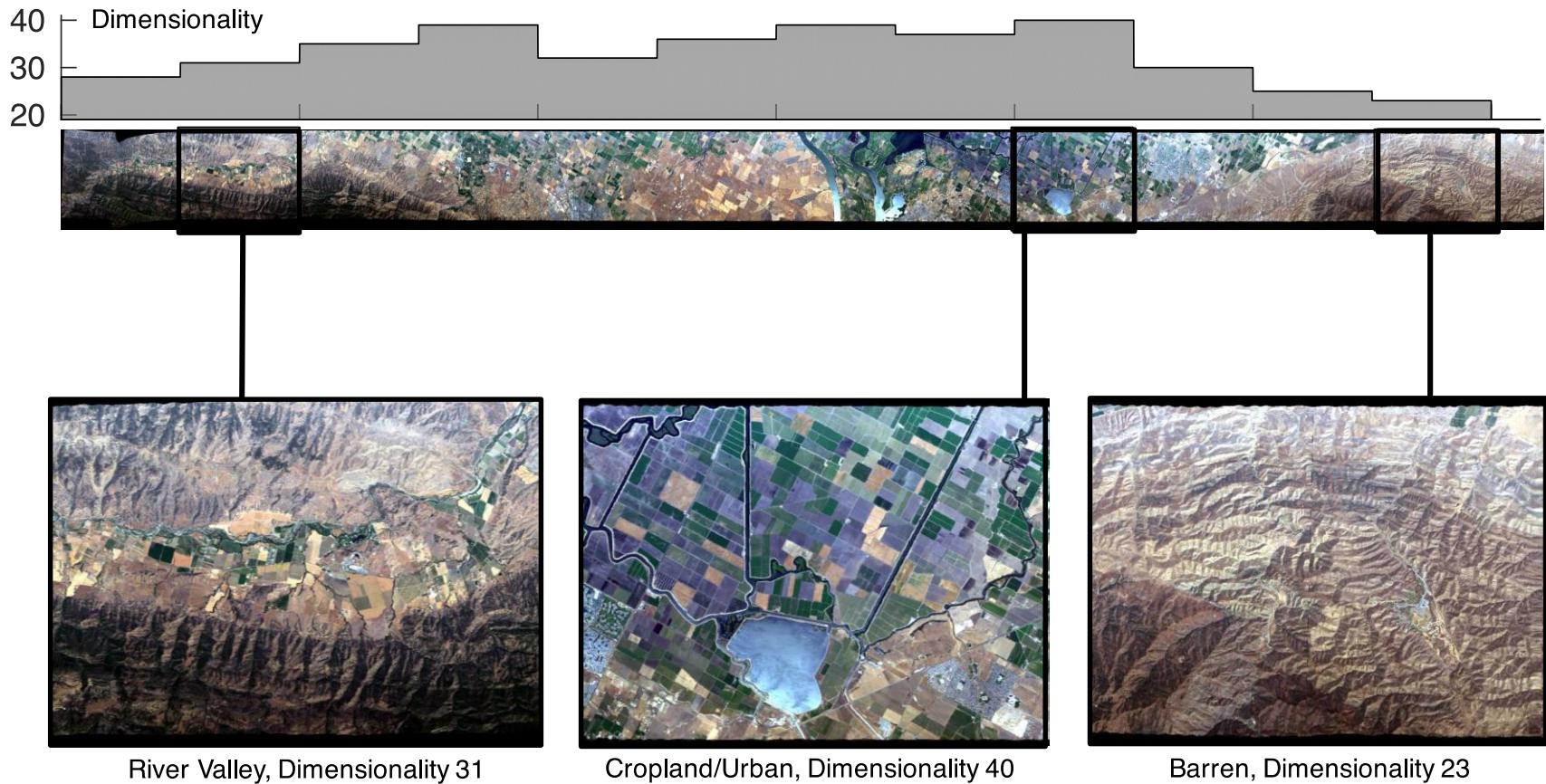


# Agenda

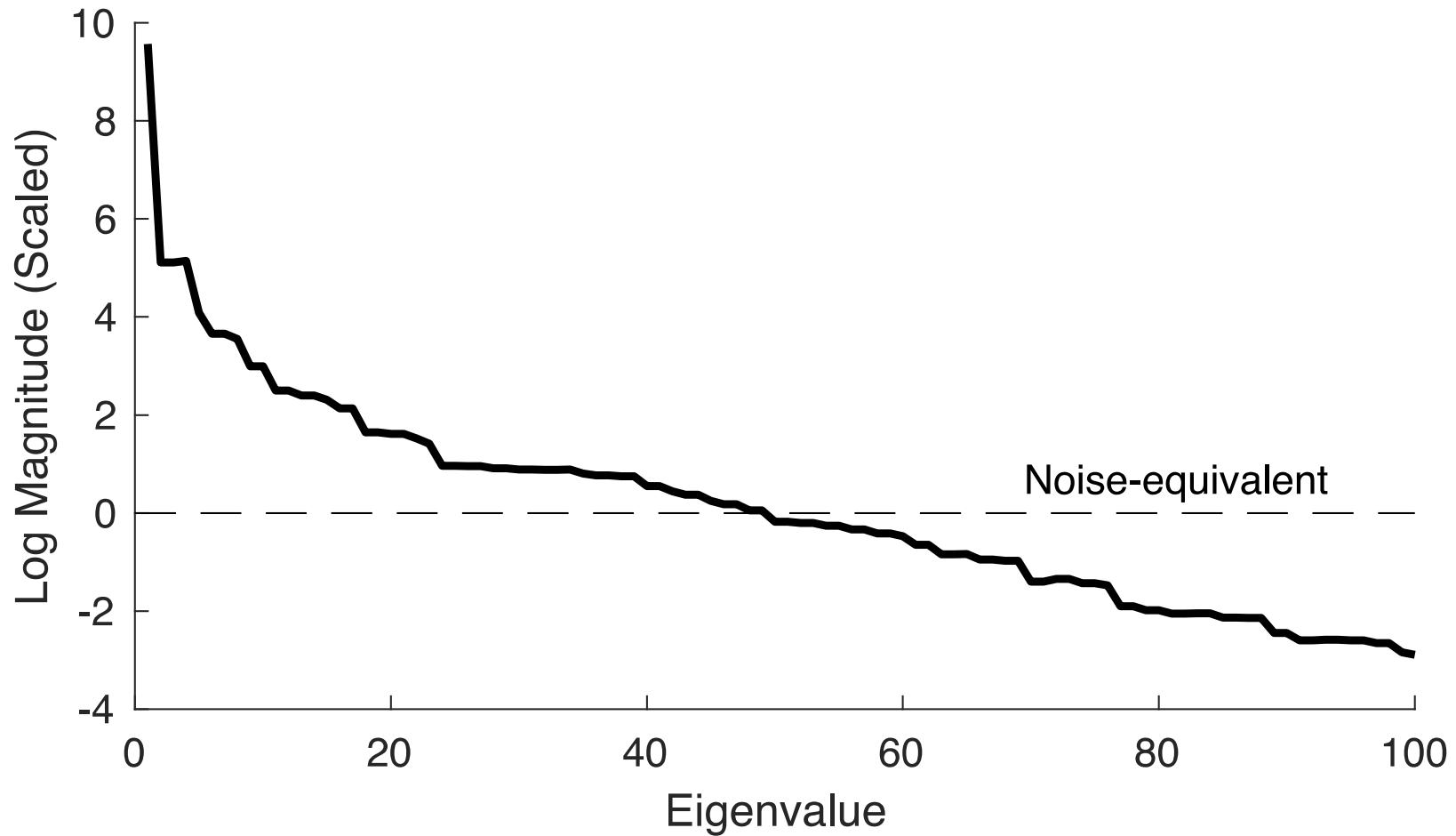
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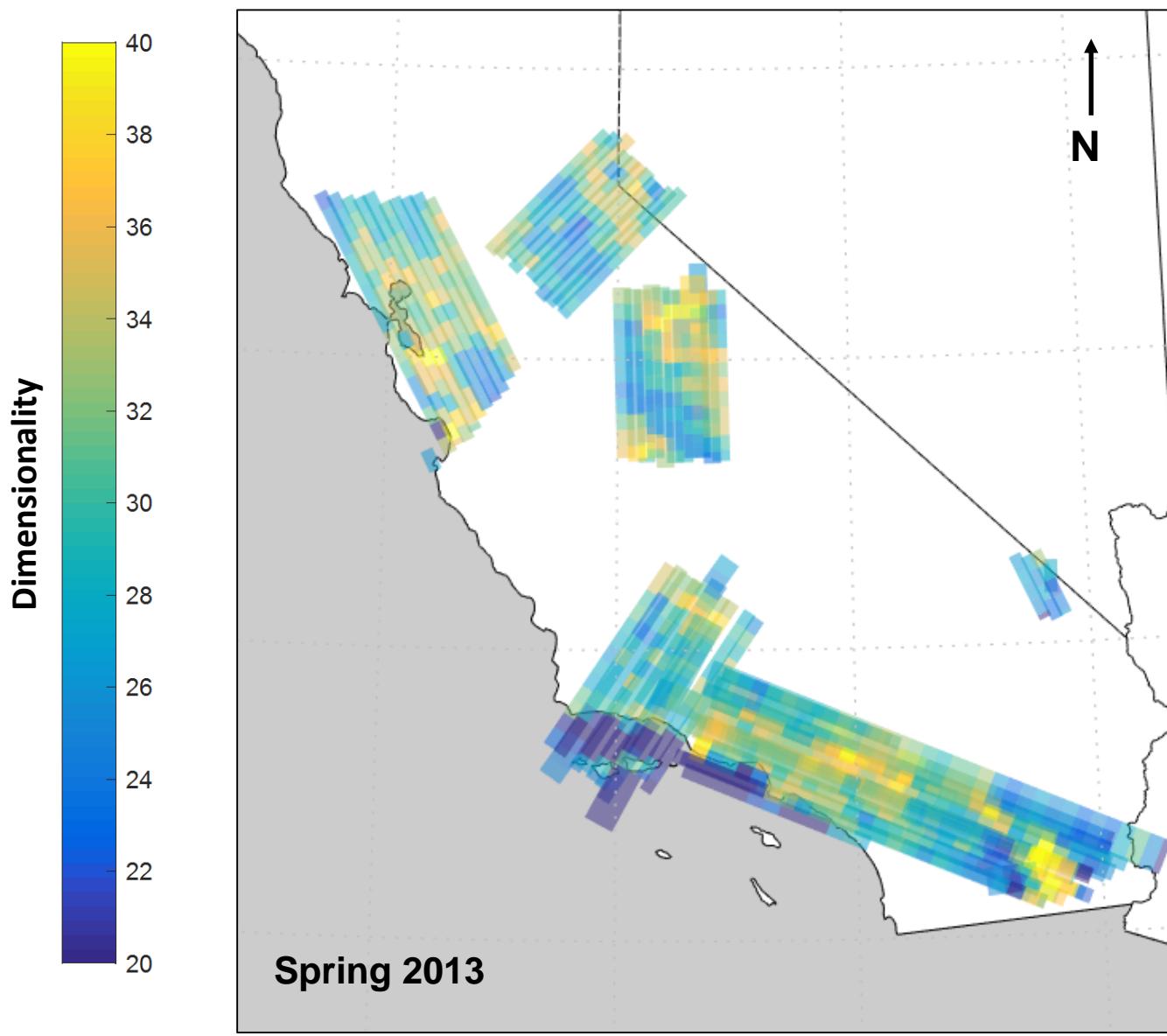


# Flightline Segments

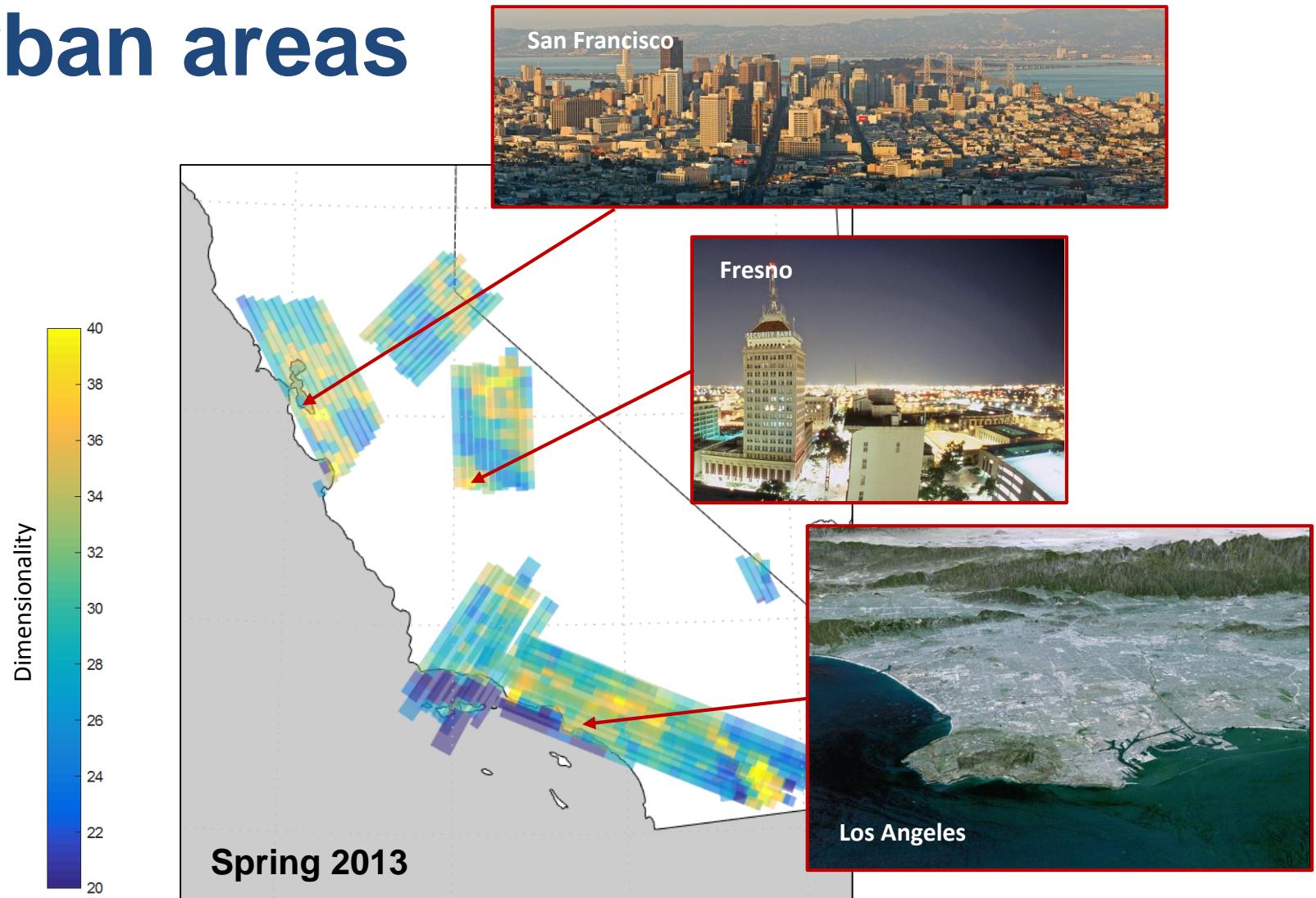


# Eigenvalue decay



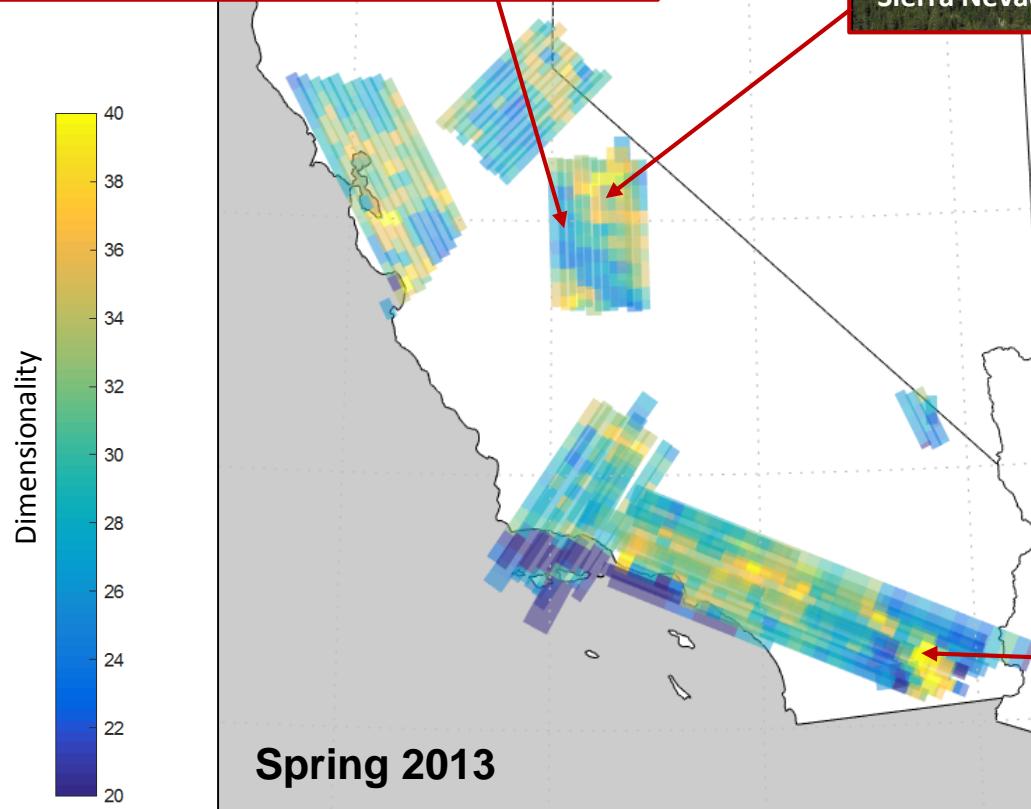


# Urban areas



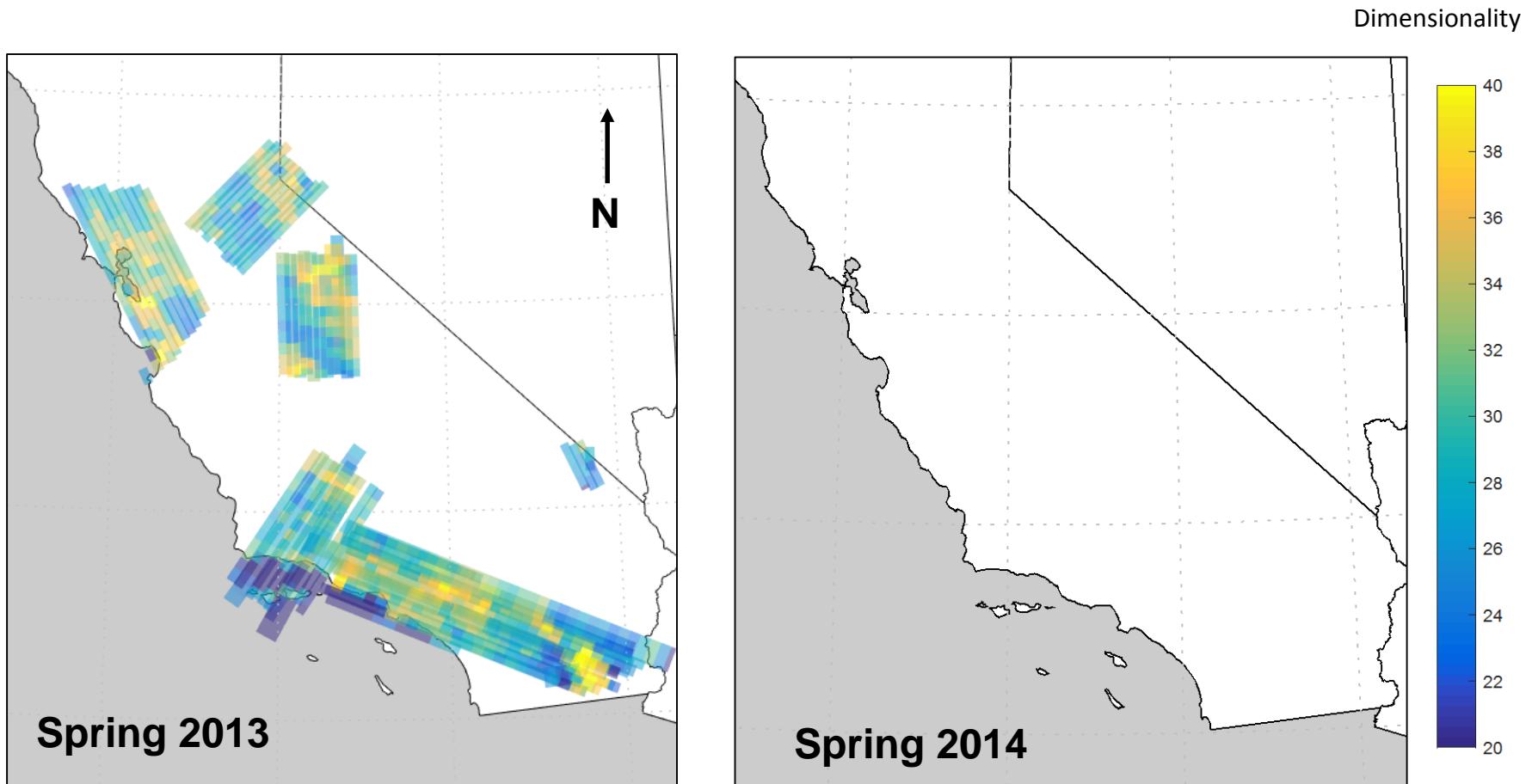
Images: Wikimedia, Christian Mehlführer, Jmora24, NASA/JPL/NIMS



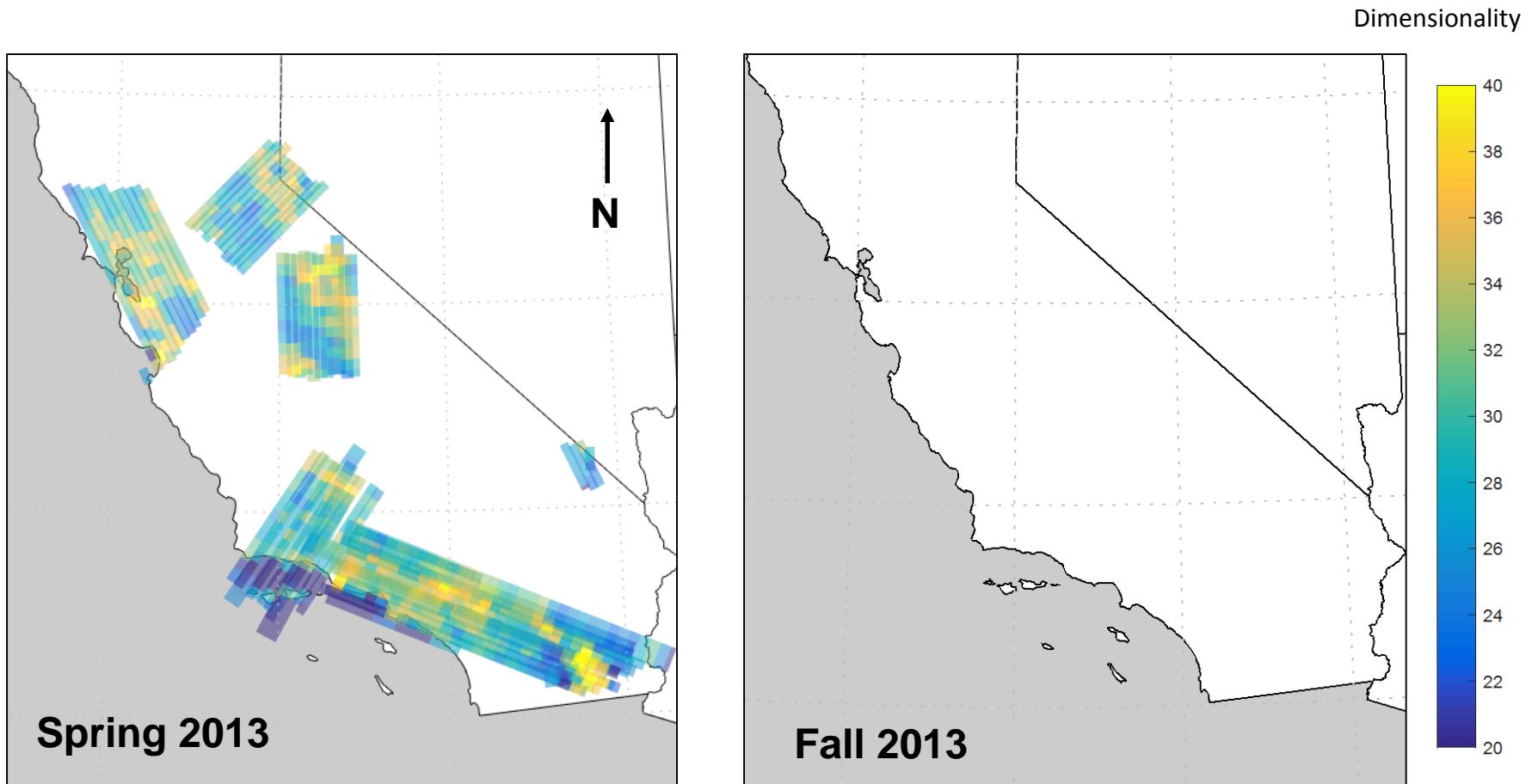


Images: Google / NASA / Sierra Nevada Photo by DAVID ILIFF. License: CC-BY-SA 3.0

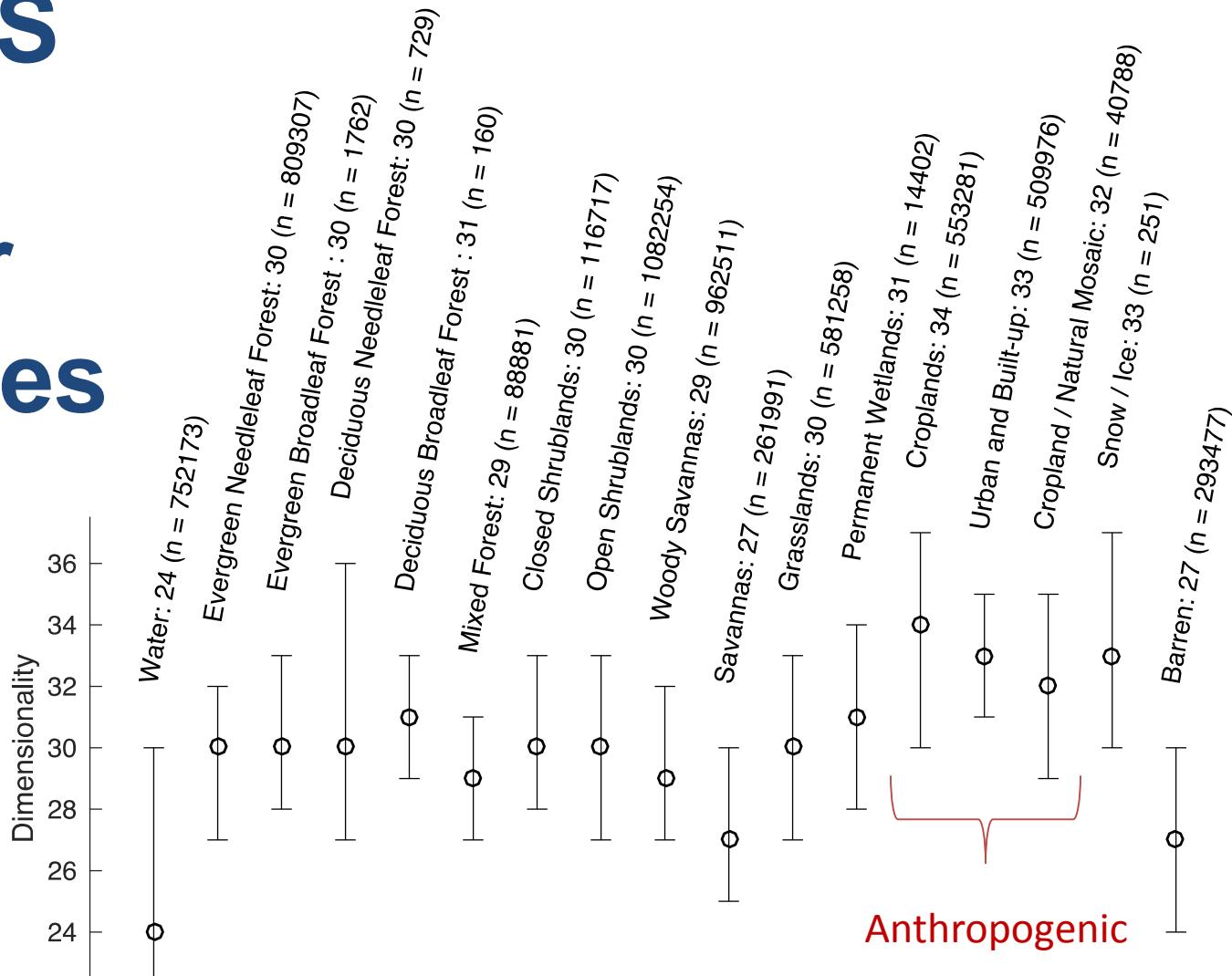
# Variability across years



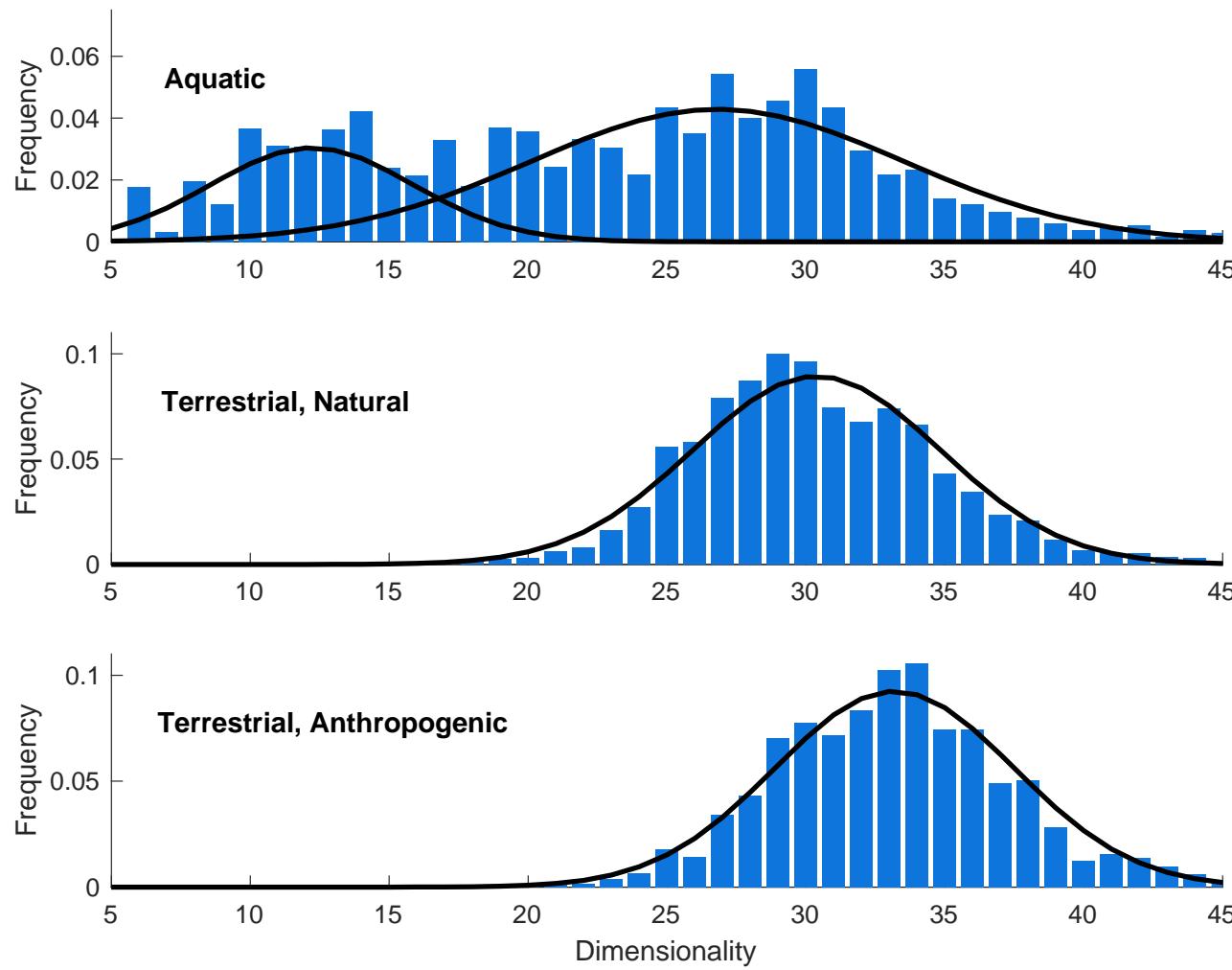
# Variability across seasons



# MODIS Land Cover Classes



# Aquatic and Terrestrial Surfaces



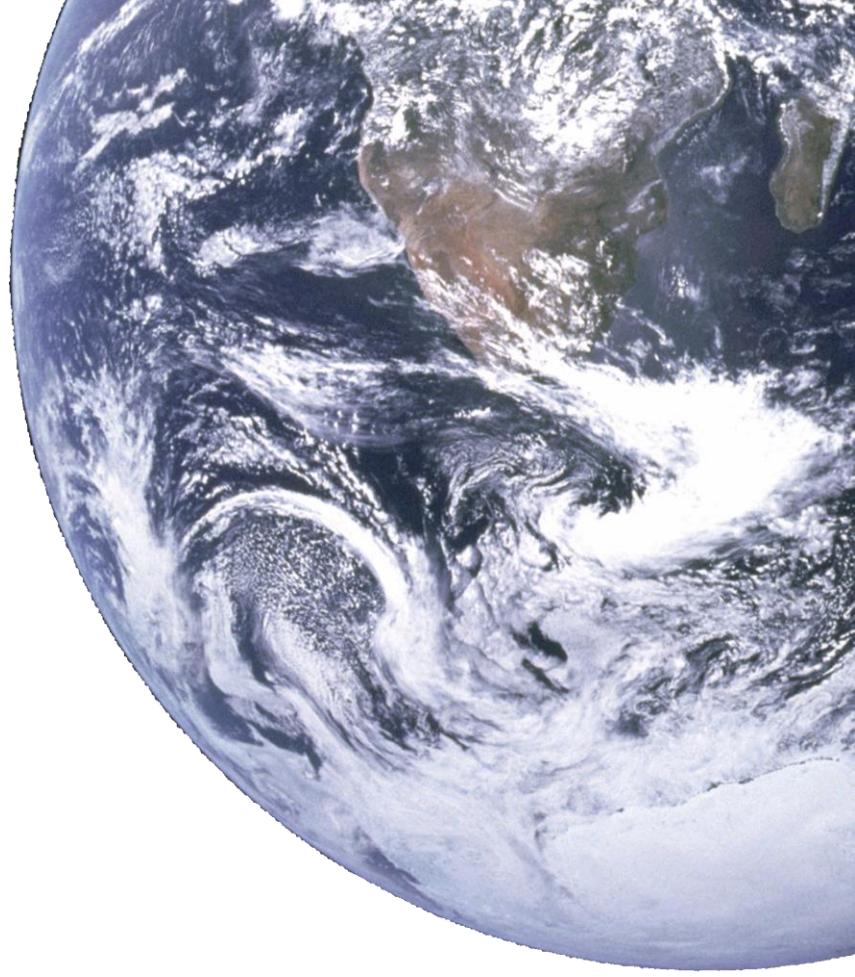
# Summary of HyspIRI results

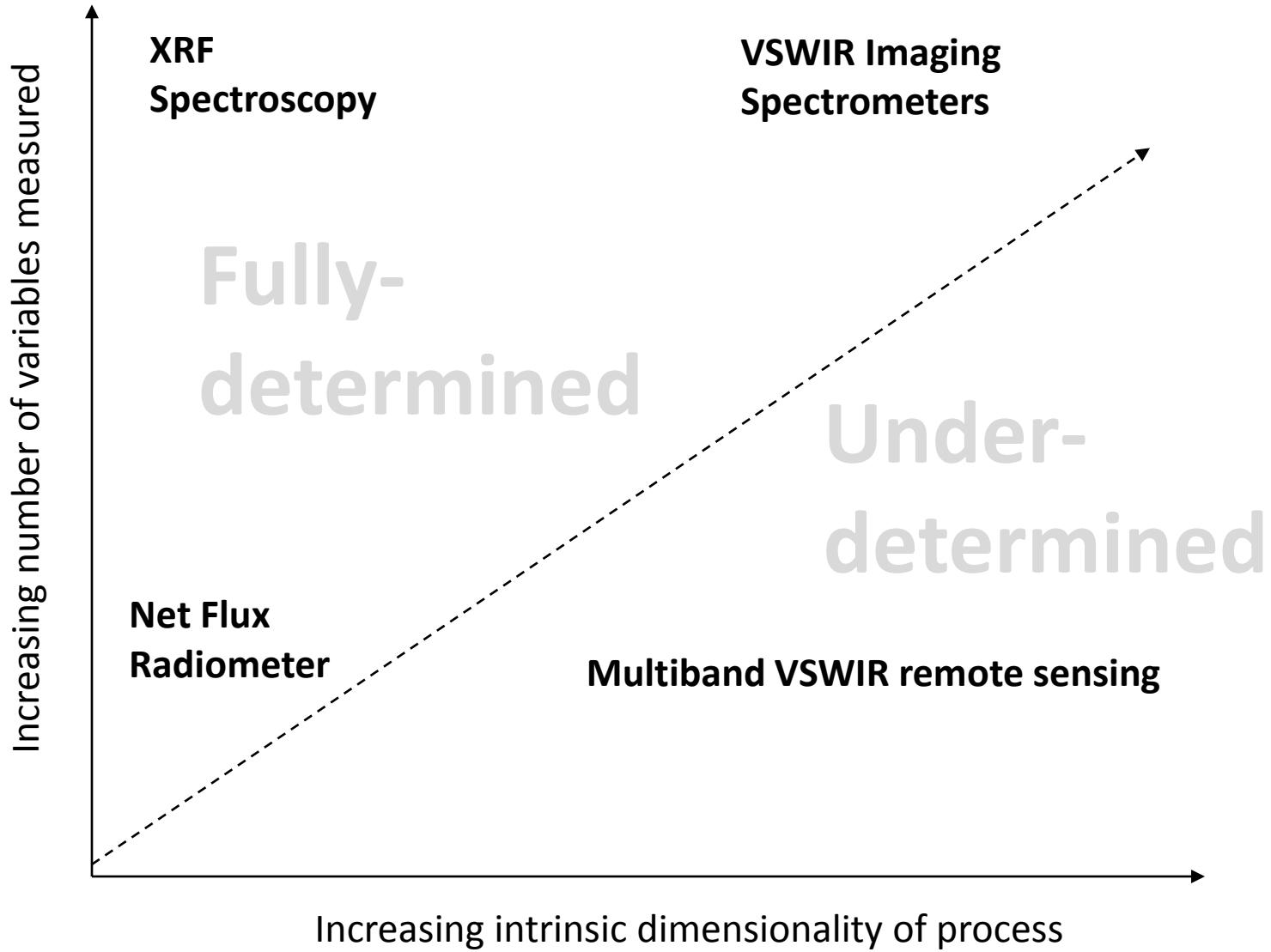
- Results are comparable to Boardman & Green 1999
- Diversity of whole far higher than individual segments
- We find the highest diversity in urban areas, the lowest in aquatic environments
- Spectroscopic measurements are a powerful tool to fully measure the information present in Earth's high-dimensional radiant light field



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# The power of VSWIR Imaging Spectroscopy

- Provides stable, *numerically-overdetermined* measurements
- Can test and confirm modeling assumptions
- Can falsify or recognize departures from modeling assumptions
- Can discover unanticipated phenomena



# More information

D. R. Thompson, J. W. Boardman, M. L. Eastwood, R. O. Green (2017). “A large airborne survey of Earth’s visible-infrared spectral dimensionality,” *Optics Express*, *in press*.

AVIRIS-C data is available from  
<http://aviris.jpl.nasa.gov>

AVIRIS-NG data is available from  
<http://avirisng.jpl.nasa.gov>



# Thanks!

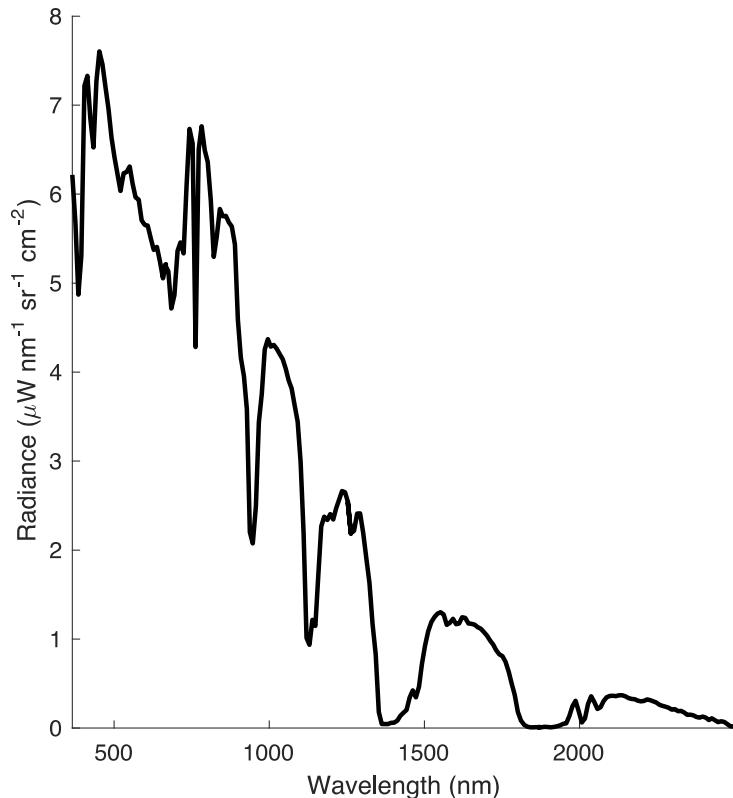
- **NASA Earth Science Division** and HyspIRI preparatory campaign
- **The AVIRIS-C and AVIRIS-NG flight teams**, including Sarah Lundein, Ian McCubbin, and Charles Sarture.
- **The EARSeL-SIG organizers** and the University of Zurich
- **Joseph W. Boardman** for his insight and tutelage



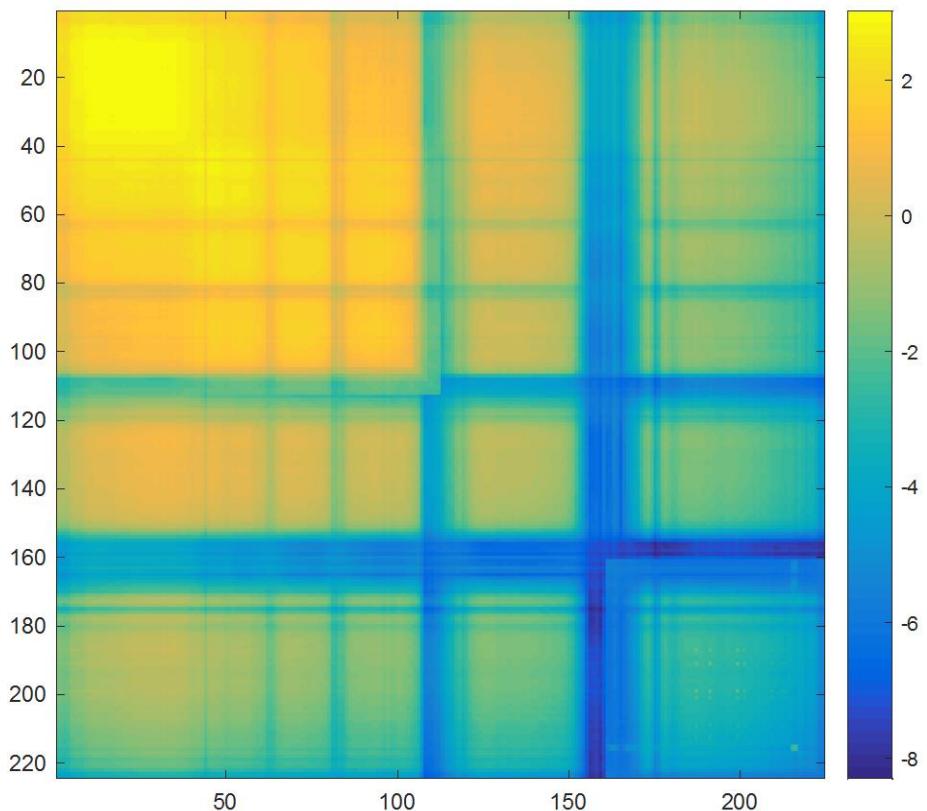
# Backup

# Mean and covariance structure

Mean radiance



Covariance matrix



# Top 9 Eigenvectors

